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Delamination vs. break-off: the fate of continental collision

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[1] The fate of a convergent continental margin is investigated. We perform a set of 2D numerical models to study how and why continental collision can evolve in different scenarios. Since the rheology of continental lithosphere has a major control on the dynamics of subduction, we explore a range of different lithosphere and lower crust viscosity values to understand their sensitivity on the possible scenarios. We find that with a rheologically layered crust both delamination and break-off are feasible. We identify three modes: (1) slab detachment, in which the lithospheric mantle and the crust are strongly coupled, subduction slows down and the slab eventually breaks; (2) delamination of the lithospheric mantle that separates from the crust and continue to subduct and (3) an intermediate mode where the lithospheric mantle and the crust remain partially coupled, resulting in an initial stage of delamination followed by the slow down and cessation of subduction.
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1. Introduction

[2] The arrival of continental lithosphere at a subduction zone provides a dramatic change in the dynamics of a convergent system. The transition from oceanic subduction to continental collision is complex and diverse, and may evolve into different scenarios (Fig. 1). The first possibility is that the continental material keeps subducting up to mid upper mantle depth, due to negative pull exerted by the previously subducted oceanic lithosphere, even though its positive buoyancy opposes sinking [*van den Beukel and Wortel*, 1987; *Ranalli et al.*, 2000; *Regard et al.*, 2003; *Toussaint et al.*, 2004]. A second possible scenario is that the negatively buoyant, hanging oceanic slab produces high tensile stresses and detaches from the buoyant continental part [*Wortel and Spakman*, 1992; *Davies and Von Blanckenburg*, 1995]. Yet another possibility is the delamination of the mantle lithosphere from the continental crust, through a mechanical decoupling between them [*Bird*, 1979; *Cloos*, 1993; *Chemenda et al.*, 1996; *Meissner and Mooney*, 1998; *Kerr and Tarney*, 2005; *Capitanio et al.*, 2010]. These different end-members of continental subduction are expected to produce contrasting kinematics and deformation patterns at the surface. In the collision and break-off scenario, the trench is likely to advance [*Royden*, 1993; *Regard et al.*, 2008; *Magni et al.*, 2012], and horizontal compressive stresses are expected, resulting in significant shortening. This may explain the tendency of the continental plate to indent into the overriding plate as observed for the Arabia and India. On the other hand, in the delamination scenario, the slab, which consists of dense lithospheric mantle peeled away from the crust, retreats [*Royden*, 1993; *Göğüş et al.*, 2011]. This causes an extensional regime within the overriding plate and thermal uplift. This model has been applied to the Northern Apennines [*Channell and Mareschal*, 1989; *Chiarabba et al.*, 2009] or Anatolia [*Göğüş and Pysklywec*, 2008]. Which of these scenarios takes place depends on a variety of factors including the plate convergence rate, and both composition and thermal structure of the continental lithosphere.

[3] The strength of continental lithosphere depends on many intrinsic parameters, such as mineralogical composition, structure, grain size, thermal history, fluid content and pore fluid pressure. Different rheological models have been proposed to infer the strength of the lithosphere from these parameters [e.g., *Jackson*, 2002; *Afonso and Ranalli*, 2004; *Handy and Brun*, 2004; *Burov*, 2011]. Our elusive knowledge of those parameters complicates modelling the continental subduction dynamics. Moreover, continents differ from each other because of their diverse formation, composition, age and thermal history, all features that affect the rheological properties of the lithosphere. Therefore, a wide range of viable strength profiles exists for continental lithosphere.

[4] A widely recognized continental rheology model (known as "jelly sandwich") assumes a strong crust and a strong lithospheric mantle that are separated by a weak ductile layer at the base of the continental crust [*Ranalli*, 1995; *Handy and Brun*, 2004; *Burov*, 2011]. The weakness of this ductile layer is strongly dependent on the composition of the lower crust (e.g., quartz, diabase, feldspar, quartz-diorite, etc.) and the thermal gradient, and therefore lithospheric age [*Watts*, 2001; *Burov*, 2011].

[5] Here, we study the effect of such strength differences on the dynamics of continental subduction. We present new models to understand under which conditions delamination or slab detachment occur. Our results provide new quantitative constrains on the rheological characteristics of continental crust and how it controls different scenarios of continental collision.

2. Numerical Method

[6] To study subduction dynamics we use the finite element code Citcom that solves for conservation of mass, momentum, energy and composition in a Cartesian geometry [*Moresi and Solomatov*, 1995; *Moresi and Gurnis*, 1996; *Zhong et al.*, 2000] (see *Magni et al.* [2012] for a more detailed description of the used method and parameters values).

All Supporting Information may be found in the online version of this article.
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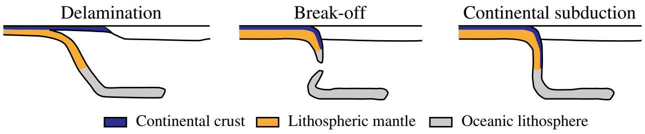

Figure 1. Schematic diagram of different continental subduction scenarios: delamination versus break-off.

[7] Subduction is modelled in a 2D rectangular domain with a depth of 660 km and an aspect ratio of 1:5 (Fig. 2). The bottom of the domain corresponds to the upper-lower mantle discontinuity. The top boundary has a fixed temperature of 0°C, whereas the other boundaries have a fixed mantle temperature $T_m = 1350°C$. Velocity boundary conditions are free-slip on all but the bottom boundary, where a no-slip condition is applied to model the effect of the high viscosity lower mantle acting as a rigid boundary (Fig. 2). The assumption that no vertical displacement is allowed at the surface (*i.e.*, free slip condition) oversimplifies the system, which would require a free surface boundary to simulate a more realistic condition. However we do not expect any first order effect on the dynamics of continental subduction. The subducting lithosphere is oceanic with a continental block embedded, whereas the overriding plate is totally continental. Initially, the oceanic slab extends to ~300 km depth to allow enough pull to subduct the slab without imposing any external forces. The initial temperature field for the oceanic lithosphere is calculated following the half-space cooling solution for a 70-Myr old plate [*Turcotte and Schubert*, 2002]. The continental lithosphere has a 40-km thick buoyant crust, and its temperature extends linearly from 0°C at the surface to T_m at 150 km depth. The passive margin is designed simply tapering the continent at its junction with the ocean and not including a wider transitional passive margin geometry. The size of the computational mesh elements varies from 15x15 km^2 to 5x5 km^2, where the better resolution is used to resolve the plate contact zone, where a narrow weak zone area is used to decouple the converging plates (see [*Magni et al.*, 2012] for details).

[8] We apply diffusion creep, dislocation creep, and a stress-limiting rheology to define material strength (see [*van Hunen and Allen*, 2011] for details). We simulate the presence of a rheologically weak lower crust in the continental subducting plate by defining in the initial setup a layer between 20 and 40 km depth with an imposed fixed viscosity (η_l; Fig. 2). This layer is then allowed to deform during the evolution of subduction. Since a wide range of different strength profiles is likely for continental lithosphere, in our models we systematically vary the maximum viscosity of the lithosphere η_s (ranging between 10^{22} Pa s and 10^{24} Pa s) and the viscosity of the lower crust η_l (ranging between 10^{19} Pa s and 10^{24} Pa s).

3. Results

[9] We performed a sensitivity study to investigate the role of both η_l and η_s (Table 1 in the Supporting Information) on the style of subduction. The resulting models can be subdivided into two end-members: break-off and delamination.

[10] In both cases the dynamics prior to continental collision is similar: the oceanic subduction occurs, the slab rolls back causing trench retreating. Then, subduction velocity sharply decreases when collision occurs, because the positive buoyancy of the continental material acts as a resisting force to subduction (Fig. 3). At this point, the dynamics starts to differ between the two end-member styles.

[11] For a high lower crustal viscosity, the shallow buoyant block of continental material and the dense oceanic part of the slab at depth interact for several million years, until thermal weakening and high tensile stresses lead the necking and break-off of the slab (Fig. 3a). The trench migration shows a reversal of direction when the continent enters the subduction zone: during oceanic subduction the trench retreats (i.e., 'slab roll-back'), whereas, during collision it starts to advance and it keeps advancing until the break-off occurs (Fig. 3a and 3d).

[12] Decreasing lower crustal viscosity favours delamination: in the subducting continent, the upper crust separates from the mantle lithosphere. The slab, now primarily formed by the fully decoupled lithospheric mantle, can continue to subduct (Fig. 3c). In fact, it rolls back and therefore the delamination front, where the lithospheric mantle detaches from the overlying crust, migrates away from the original suture zone (Fig. 3c and 3f).

[13] Some models show an intermediate behaviour in which crust and lithospheric mantle remain partially coupled. Therefore, the positive buoyancy of the continental crust is still a component of the forces acting on subduction. This results in an initial delamination followed by the slow down/stop of subduction until the oceanic part of the slab detaches from the shallower continental part (i.e., break-off; Fig. 3b). In this style, the delamination front slightly

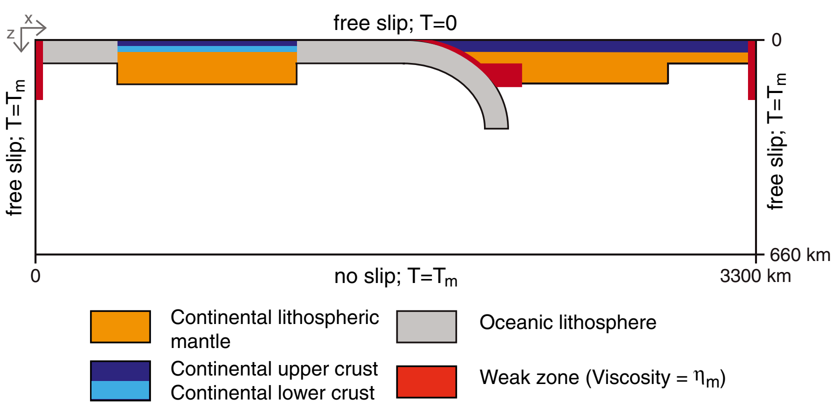

Figure 2. Initial model setup illustrating dimensions, mechanical and thermal boundary conditions, and lithologies. Areas with an imposed low viscosity (i.e. the reference mantle viscosity) are outlined in red.

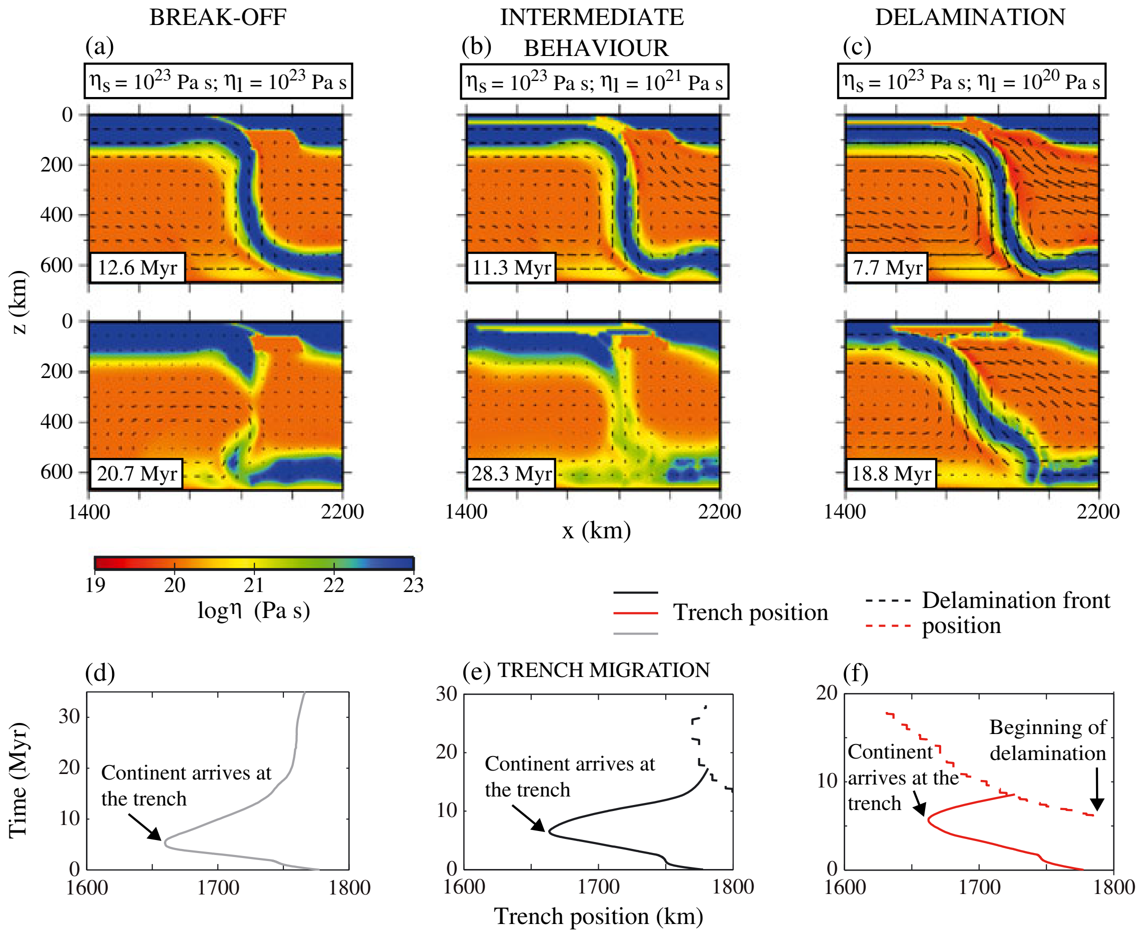

Figure 3. The three different resulting scenarios: break-off (a, d), intermediate behaviour (b, e) and delamination (c, f). (a) Viscosity plot of model with $\eta_s = 10^{23}$ Pa s and $\eta_l = 10^{23}$ Pa s; (b) viscosity plot of model with $\eta_s = 10^{23}$ Pa s and $\eta_l = 10^{21}$ Pa s and (c) viscosity plot of model with $\eta_s = 10^{23}$ Pa s and $\eta_l = 10^{20}$ Pa s. (d, e, f) Trench position during model evolution for the 3 modes: solid lines show trench position; dotted lines indicate the position of the delamination front.

migrates away from the suture zone initially, but later remains stationary (Fig. 3e). The amount of migration of the delamination front in this kind of models varies between 10-80 km depending on the values of η_l and η_s.

[14] Results are summarized in Fig. 4, which illustrates that, in general, low values of η_l favour delamination, and high values give break-off. In particular, for the studied range of η_s, we find that for $\eta_l \leq 10^{20}$ Pa s delamination always occurs, whereas slab detachment always occurs for $\eta_l \geq 5\text{x}10^{21}$ Pa s. For η_l between these two values all the three scenarios are feasible: break-off, delamination and the intermediate behaviour. Since delamination is incomplete and minor in the intermediate models, and break-off eventually occurs, we consider this style to fall within the field of break-off. We fitted the results of the two-layered crust models to a parameter D that follows a linear scaling law:

$$D = A * log_{10}(\eta_l) + B * log_{10}(\eta_s)$$

where the coefficients are: A = 0.0718 and B = -0.0208. D < 1 corresponds to the delamination process, while for D > 1 break-off is likely to occur.

4. Discussion and Conclusions

[15] Our results show that, by changing the viscosity profile of the continental lithosphere, different collision scenarios are possible: from continuation of subduction through delamination to subduction cessation and slab break-off. Delamination is favoured by a low viscosity of the lower crust, because this makes the mechanical decoupling between the crust and the lithospheric mantle easier. Furthermore, a higher slab viscosity requires a higher viscosity of the lower crust to favour break-off over delamination (Fig. 4). This is valid up to $\eta_l = 5\text{x}10^{21}$ Pa s, but above this value crust and the lithospheric mantle are too strongly coupled for delamination.

[16] Previous numerical and analogue studies on continental collision showed that both delamination [*Schott and Schmeling*, 1998; *Morency and Doin*, 2004; *Göğüş and Pysklywec*, 2008; *Valera et al.*, 2008; *Göğüş et al.*, 2011; *Bajolet et al.*, 2012; *Ueda et al.*, 2012] and slab detachment [*Davies and Von Blanckenburg*, 1995; *Wong A Ton and Wortel*, 1997; *Gerya et al.*, 2004; *Toussaint et al.*, 2004; *Andrews and Billen*, 2009; *Burkett and Billen*, 2009; *Duretz et al.*, 2011; *van Hunen and Allen*, 2011] are likely to occur. The major control of the lower crustal strength on the evolution of delamination that we observe is consistent with previous models [*Schott and Schmeling*, 1998; *Morency and Doin*, 2004]. Values of lower crust viscosity necessary to obtain the delamination of the lithospheric mantle of 2 x 10^{20} Pa s [*Gemmer and Houseman*, 2007], 10^{20} Pa s [*Valera et al.*, 2008] and from 10^{20} to 10^{21} Pa s [*Schott*

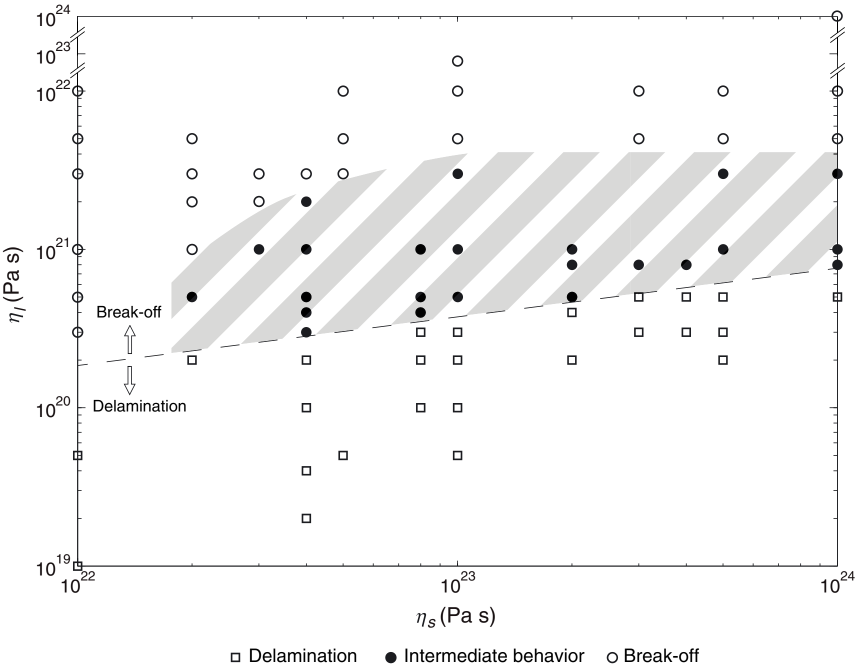

Figure 4. All model results and the calculated scaling law (dotted line) in a slab viscosity (η_s) vs. lower crust viscosity (η_l) plot. Dots represent the break-off mode (filled dots for the intermediate behaviour, outlined also by the grey banded area) and squares represent the delamination mode.

and Schmeling, 1998] are in agreement with our results. Similarly, *Baes et al*. [2011] found that delamination occurs for values of lower crust to upper lithospheric mantle viscosity ratio equal to or smaller than 0.006. In a more complex rheology setup, *Ueda et al*. [2012] observed in some models the formation of a low-viscosity conduit across the lithospheric mantle that allows delamination. *De Franco et al*. [2008] explore the importance of the width and rheology of the contact zone. The convergence rate is an additional feature that can have an influence on the possibility for the delamination to occur. *Göğüş et al*. [2011] found that a low convergence velocity favours delamination. However, the main feature that governs the evolution of continental collision remains the rheology of the crust.

[17] An important difference between the scenarios that we observe lies in the trench migration. In the case of delamination, the continuation of subduction leads to a roll-back of the slab, hence, the delamination front propagates along the boundary between crust and lithospheric mantle, migrating away from the overriding plate. In between the original collision location and the delamination front the lithosphere is very thin, since only the upper crust remains, while the lithospheric mantle subducts. In the intermediate models, the delamination front cannot migrate much, since the lithospheric mantle is coupled with the buoyant continental crust. Finally, the slab migrates towards the overriding plate (advancing) in the models with slab detachment. This is further discussed in *Magni et al*. [2012].

[18] Models with a strong lower crust are probably suitable for old continental plates, such as cratons that are characterized by a cold geotherm [*Burov*, 2011]. On the contrary, for young continents, the most common rheology model suggests a stratified structure of the lithosphere, where a weak ductile level may lead to a mechanical decoupling between the layers [*Burov*, 2011].

[19] A good example of these different dynamics is found in the central Mediterranean subduction system. In the southern part, the African slab is detached due to the entrance of the African craton in the subduction zone [*Wortel and Spakman*, 2000]. On the contrary, in several areas of the Mediterranean, such as the Apennines, Hellenides, Betics and Anatolia [*Channell and Mareschal*, 1989; *Comas et al*., 1992; *Brun and Faccenna*, 2008; *Göğüş and Pysklywec*, 2008; *Chiarabba et al*., 2009; *Faccenda et al*., 2009; *Göğüş et al*., 2011; *Gray and Pysklywec*, 2012], onset of continental subduction caused delamination. In the Apennines, the delamination scenario is favoured as the Apulian crust has been affected by the relatively recent Variscan orogeny. In addition, several seismological studies show that beneath the northern Apennines, delamination is ongoing, separating the crust from the mantle [e.g., *Chiarabba et al*., 2009; *Di Luzio et al*., 2009].

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References

Afonso, J. C., and G. Ranalli (2004), Crustal and mantle strengths in continental lithosphere: is the jelly sandwich model obsolete?, *Tectonophys.*, *394*(3-4), 221–232, doi:10.1016/j.tecto.2004.08.006.

Andrews, E. R., and M. I. Billen (2009), Rheologic controls on the dynamics of slab detachment, *Tectonophys.*, *464*(1-4), 60–69.

Baes, M., R. Govers, and R. Wortel (2011), Switching between alternative responses of the lithosphere to continental collision, *Geophys. J. Int.*, *187*(3), 1151–1174.

Bajolet, F., J. Galeano, F. Funiciello, M. Moroni, A.-M. Negredo, and C. Faccenna (2012), Continental delamination: Insights from laboratory models, *Geochem. Geophys. Geosyst.*, *13*, Q02009, doi:10.1029/2011GC003896.

Bird, P. (1979), Continental delamination and the Colorado Plateau, *J. Geophys. Res.*, *84*(B13), 7561–7571.
Brun, J. P., and C. Faccenna (2008), Exhumation of high-pressure rocks driven by slab rollback, *Earth Planet. Sci. Lett.*, *272*(1-2), 1–7.
Burkett, E. R., and M. I. Billen (2009), Dynamics and implications of slab detachment due to ridge-trench collision, *J. Geophys. Res. Solid Earth*, *114*, B12402, doi:10.1029/2009JB006402.
Burov, E. B. (2011), Rheology and strength of the lithosphere, *Mar. Pet. Geol.*, *28*(8), 1402–1443.
Capitanio, F. A., G. Morra, S. Goes, R. F. Weinberg, and L. Moresi (2010), India-Asia convergence driven by the subduction of the Greater Indian continent, *Nat. Geosci.*, *3*(2), 136–139.
Channell, J. E. T., and J. C. Mareschal (1989), Delamination and asymmetric lithospheric thickening in the development of the Tyrrhenian Rift, *Geol. Soc., London, Spec. Publ.*, *45*(1), 285–302.
Chemenda, A. I., M. Mattauer, and A. N. Bokun (1996), Continental subduction and a mechanism for exhumation of high-pressure metamorphic rocks: new modelling and field data from Oman, *Earth Planet. Sci. Lett.*, *143*(1-4), 173–182.
Chiarabba, C., P. De Gori, and F. Speranza (2009), Deep geometry and rheology of an orogenic wedge developing above a continental subduction zone: Seismological evidence from the northern-central Apennines (Italy), *Lithosphere*, *1*(2), 95–104.
Cloos, M. (1993), Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts, *Geol Soc Am Bull*, *105*(6), 715–737.
Comas, M. C., V. García-Dueñas, and M. J. Jurado (1992), Neogene tectonic evolution of the Alboran Sea from MCS data, *Geo-Mar. Lett.*, *12*(2), 157–164.
Davies, J. H., and F. Von Blanckenburg (1995), Slab breakoff - A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens, *Earth Planet. Sci. Lett.*, *129*(1-4), 85–102.
De Franco, R., R. Govers, and R. Wortel (2008), Dynamics of continental collision: influence of the plate contact, *Geophys. J. Int.*, *174*(3), 1101–1120.
Di Luzio, E., G. Mele, M. M. Tiberti, G. P. Cavinato, and M. Parotto (2009), Moho deepening and shallow upper crustal delamination beneath the central Apennines, *Earth Planet. Sci. Lett.*, *280*(1-4), 1–12.
Duretz, T., T. V. Gerya, and D. A. May (2011), Numerical modelling of spontaneous slab breakoff and subsequent topographic response, *Tectonophys.*, *502*(1-2), 244–256.
Faccenda, M., G. Minelli, and T. V. Gerya, (2009), Coupled and decoupled regimes of continental collision: Numerical modeling. *Earth Planet. Sci. Lett.*, *278*, 337–349.
Gemmer, L., and G. A. Houseman (2007), Convergence and extension driven by lithospheric gravitational instability: evolution of the Alpine–Carpathian–Pannonian system, *Geophys. J. Int.*, *168*(3), 1276–1290.
Gerya, T. V., D. A. Yuen, and W. V. Maresch (2004), Thermomechanical modelling of slab detachment, *Earth Planet. Sci. Lett.*, *226*(1-2), 101–116.
Göğüş , O. H., and R. N. Pysklywec (2008), Mantle lithosphere delamination driving plateau uplift and synconvergent extension in eastern Anatolia, *Geology*, *36*(9), 723–726.
Göğüş , O. H., R. N. Pysklywec, F. Corbi, and C. Faccenna (2011), The surface tectonics of mantle lithosphere delamination following ocean lithosphere subduction: Insights from physical-scaled analogue experiments, *Geochem. Geophys. Geosyst.*, *12*, Q05004, doi:10.1029/2010GC003430.
Gray, R., and R. N. Pysklywec (2012), Geodynamic models of mature continental collision: Evolution of an orogen from lithospheric subduction to continental retreat/delamination, *J. Geophys. Res.*, *117*(B3), B03408, doi:10.1029/2011JB008692.
Handy, M. R., and J. P. Brun (2004), Seismicity, structure and strength of the continental lithosphere, *Earth Planet. Sci. Lett.*, *223*(3-4), 427–441.
Jackson, J. (2002), Strength of the continental lithosphere: time to abandon the jelly sandwich?, GSA Today, September, 4-10.
Kerr, A. C., and J. Tarney (2005), Tectonic evolution of the Caribbean and northwestern South America: The case for accretion of two Late Cretaceous oceanic plateaus, *Geology*, *33*(4), 269–272.
Magni, V., J. van Hunen, F. Funiciello, and C. Faccenna (2012), Numerical models of slab migration in continental collision zones, *Solid Earth*, *3*(2), 293–306.
Meissner, R., and W. Mooney (1998), Weakness of the lower continental crust: a condition for delamination, uplift, and escape, *Tectonophys.*, *296*(1-2), 47–60.
Morency, C., and M. P. Doin (2004), Numerical simulations of the mantle lithosphere delamination, *J. Geophys. Res.*, *109*(B3), B03410, doi:10.1029/2003jb002414.
Moresi, L., and V. S. Solomatov (1995), Numerical investigation of 2d convection with extremely large viscosity variations, *Phys. Fluids*, *7*(9), 2154–2162.
Moresi, L., and M. Gurnis (1996), Constraints on the lateral strength of slabs from three-dimensional dynamic flow models, *Earth Planet. Sci. Lett.*, *138*(1,Äì4), 15–28.
Ranalli, G. (1995), *Rheology of the Earth*, 2nd ed., Chapman & Hall, London.
Ranalli, G., R. Pellegrini, and S. D'Offizi (2000), Time dependence of negative buoyancy and the subduction of continental lithosphere, *J. Geodyn.*, *30*(5), 539–555.
Regard, V., C. Faccenna, O. Bellier, and J. Martinod (2008), Laboratory experiments of slab break-off and slab dip reversal: insight into the Alpine Oligocene reorganization, *Terra Nova*, *20*(4), 267–273.
Regard, V., C. Faccenna, J. Martinod, O. Bellier, and J. C. Thomas (2003), From subduction to collision: Control of deep processes on the evolution of convergent plate boundary, *J Geophys. Res. Solid Earth*, *108*(B4).
Royden, L. H. (1993), The tectonic expression slab pull at continental convergent boundaries, *Tectonics*, *12*(2), 303–325.
Schott, B., and H. Schmeling (1998), Delamination and detachment of a lithospheric root, *Tectonophys.*, *296*(3-4), 225–247.
Toussaint, G., E. Burov, and L. Jolivet (2004), Continental plate collision: Unstable vs. stable slab dynamics, *Geology*, *32*(1), 33–36.
Turcotte, D. L., and G. Schubert (2002), *Geodynamics*. Cambridge University Press, Cambridge, UK.
Ueda, K., T. V. Gerya, and J. P. Burg (2012), Delamination in collisional orogens: Thermomechanical modeling, *J. Geophys. Res.*, *117*(B8), B08202, doi:10.1029/2012jb009144.
Valera, J.-L., A.-M. Negredo, and A. Villaseñor (2008), Asymmetric delamination and convective removal numerical modeling: Comparison with evolutionary models for the Alboran Sea region, *Pure Appl. Geophys.*, *165*(8), 1683–1706.
van den Beukel, J., and R. Wortel (1987), Temperatures and shear stresses in the upper part of a subduction zone, *Geophys. Res. Lett.*, *14*(10), 1057–1060.
van Hunen, J., and M. B. Allen (2011), Continental collision and slab break-off: A comparison of 3-D numerical models with observations, *Earth Planet. Sci. Lett.*, *302*(1-2), 27–37.
Watts, A. B. (2001), *Isostasy and Flexure of the Lithosphere*, Cambridge University Press, Cambridge, UK.
Wong A Ton, S. Y. M., and M. J. R. Wortel (1997), Slab detachment in continental collision zones: An analysis of controlling parameters, *Geophys. Res. Lett.*, *24*(16), 2095–2098.
Wortel, M. J. R., and W. G. Spakman (1992), *Structure and Dynamics of Subducted Lithosphere in the Mediterranean Region*, edited, PAYS-BAS, North-Holland, Amsterdam.
Wortel, M. J. R., and W. Spakman (2000), Geophysics - Subduction and slab detachment in the Mediterranean-Carpathian region, *Science*, *290*(5498), 1910–1917.
Zhong, S. J., M. T. Zuber, L. Moresi, and M. Gurnis (2000), Role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection, *J Geophys. Res. Solid Earth*, *105*(B5), 11063–11082.